

TO FREEZE OR NOT TO FREEZE: THAT IS THE QUESTION
A LOOK AT FREEZEBACK LANDFILLS AND FINAL COVER DESIGNS

By

Sarah Durand, B.S.

A Project Submitted in Partial Fulfillment of the Requirements

for the Degree of

Master of Science

in

Environmental Science and Management

University of Alaska Fairbanks

December 2019

APPROVED:

Robert Perkins, Committee Chair

Srijan Aggarwal, Committee Member

David Barnes, Committee Member

Department of Civil and Environmental Engineering

Abstract

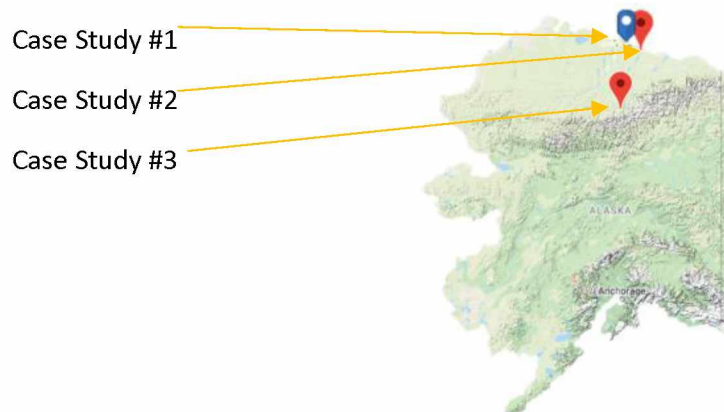
Freezeback landfills are an exciting concept but challenging in execution. There is not a single variable that leads to the success of a freezeback landfills but multiple variables in balance with each other that allow for freezeback to occur. Freezeback landfills should be engineered to the site-specific environment at the initial design stage for a better chance of success rather than following the generalized regulatory requirements. This project looked at three freezeback landfills as case studies and evaluated the final cover design of the first two in identifying parameters that lead to success in reaching and maintaining freezeback status. The parameters and research on permafrost are then applied to the third case study in a series of recommendations for consideration when designing a final cover strategy.

To Freeze or Not to Freeze: That Is the Question
A Look at Freezeback Landfills and Final Cover Designs
By Sarah Durand

Introduction

Freezeback landfills are a unique design used in northern Alaska as a means of burying waste that, in theory, have minimal effects to the surrounding environment. Many of these landfills are located in remote areas of the state that have limited to no road access. This paper will evaluate three case studies of freezeback landfills located on the north slope of Alaska. The first site is near Point McIntyre on the Beaufort Sea coastline, the second site is near Prudhoe Bay along the Sagavanirktok River, and the third site is located in the foothills of the Brooks Range near mile 285 of the Dalton Highway. The first two landfill facilities, which are Point McIntyre and the Sagvanirktok River sites, are closed landfills where the design and success of the final cover will be evaluated to make recommendations for a final cover strategy for the third site along the Dalton Highway as located on Figure 0-1.

Figure 0-1. Case Study Locations (Image ADEC SWIMS and CS Databases, accessed 12/8/2019)



The success of these freezeback landfills will be evaluated using Alaska state regulatory criteria, engineering design, final cover strategy, thermistor data collected at the sites, and finally climate and environmental data for these three sites. The goal of this research is to identify parameters that may potentially lead to success in achieving and maintaining freezeback status. The identified parameters will then be applied to the final case study presented as recommendations that the landfill can apply when considering final cover and closure.

Case Study	Latitude/Longitude	Owner	Year Constructed	Landfill Type
#1 Point McIntyre	N 70.403, W -148.679	U.S. Navy	2014	Above Ground Area Fill
#2 East Sag River	N 70.214, W -148.221	B.P. Exploration Alaska	1992	Trench and Fill
#3 117-1B	N 68.624, W -149.333	Alyeska Pipeline Services Co.	1978	Trench and Fill

Due to the extreme cost of shipping waste from these areas, it is vitally important that an economical option for waste disposal be locally available. Freezeback landfills may be a viable option for Arctic conditions, but operations continue to struggle to keep up with the changing climate. The Point McIntyre landfill represents a success for a freezeback design while the Sagavanirktok River site demonstrates how the freezeback landfill design is failing. The Dalton Highway site is contemplating final closure and is required to meet the regulatory standards for final closure of a freezeback landfill. Freezeback landfills can operate with marginal success under current climate conditions, but the future of these facilities is questionable.

The Freezeback Concept Operations and Design

Using nature to cooperate on an engineered project with a direct benefit to humans will enhance its usefulness and reduce operating costs. The engineering genius of the freezeback landfill lies in its use of the natural environment. By regulatory definition freezeback means the process of freezing solid waste in place to prevent the migration of solid waste and leachate from the designated portion of a facility (ADEC 2017). Leachate is an environmental danger because it represents a liquid that has passed through or emerged from solid waste and contains soluble, suspended, or miscible materials removed from the wastes that are highly mobile into the surrounding environment. A 2006 study in Nunavut Canada found that cadmium and lead can easily leach from open dumpsites in Arctic environments and be carried into the surrounding tundra by seasonal snow melt (Young and Lund 2006). A freezeback landfill is a unique design utilized in the northern latitudes of Alaska that interacts with permafrost. Permafrost occurs in ground where the earth remains below 0°C for more than 2 years (Runyan 2012). By design these landfills use the underlying permafrost, minimal active thaw layer, and atmospheric temperatures below freezing to hold the buried waste below freezing (32 °F) year around. Freeze point suppression is minimized by the types of wastes allowed for disposal in a Freezeback landfill. Permafrost zones underlie 80% of Alaska, including continuous (32%), discontinuous (31%), sporadic (8%), and isolated (10%) permafrost (Jorgenson et al. 2008).

Although permafrost is prevalent in Alaska, most of the permafrost observatories in the Northern Hemisphere show a substantial warming of permafrost since the 1980s (Romanovsky et al. 2014). The active layer is the surficial layer above the permafrost which thaws during summer and freezes again in the winter (Runyan 2012). Permafrost temperature at 20m depth

has been increasing between 0.28 and 0.47 °C per decade since 2000 on the North Slope of Alaska (Romanovsky et al. 2014). Research shows that surface air temperatures and snow cover play a crucial role in changes in the active layer thickness above the permafrost (Romanovsky et al. 2014). During the fall, active layer freezing proceeds both downward from the surface and upward from the underlying permafrost table (Yi et al. 2019). In a period of rapid climate and environmental changes, the freezeback landfill design may be destined to become obsolete on the Alaskan landscape due to its inability to be adaptable in a new climate regime.

There are two designs for freezeback landfills, but both rely on the underlying permafrost and cold atmospheric temperatures to keep the waste frozen. The areafill landfill places waste on top of the ground leaving the underlying vegetation and active layer in place. Berms are built on the sides with the waste placed in between them. A final cover is added over the waste with the side berms and cover taking up the active thaw layer leaving the permanently frozen waste encapsulated.

The second design type for freezeback landfills is the traditional trench and fill style where a hole is dug into the ground removing vegetation and active thaw layer and digging into the underlying permafrost. The waste is placed directly on top of the permafrost and then a final cover is added to above the original ground surface. The final cover, in theory, uptakes the active thaw layer leaving the buried waste permanently frozen. There is a wide range of waste types disposed in freezeback landfills including drilling mud wastes, construction and demolition debris, ash from waste incineration, and household municipal solid wastes to name a few. As with all other landfills in Alaska, freezeback landfills must prohibit the disposal of

hazardous waste (ADEC 2017). Most approved waste streams are outlined in the ADEC landfill permit and are specific to each landfill.

The concept of the freezeback landfill has been utilized in Alaska long before the defined term existed. Both the use of underlying permafrost as a means to manage waste and the risks to upsetting its balance were noted as far back as the first Alaska state solid waste regulation in 1973, which stated that the disposal of putrescible waste in areas subject to permafrost is restricted and shall be allowed only in conjunction with special procedures approved by the state (ADEC 1973). By 1983, there was a specific regulation to landfills located on permafrost stating the landfilled solid waste must become a fixed and integral part of the permafrost (ADEC 1983). Only a few years later in 1987 the state regulations required thermal monitoring to detect thawing, and that at the time of the landfill closure, the wastes do not cause thawing of the permafrost (ADEC 1987). The word freezeback first appeared in the 1987, regulation package, and it was in reference to a containment method of the waste by freezeback to ensure that wastes do not thaw after the landfill closure. In 1996, the Alaska regulatory agency, became more stringent on landfills underlain by permafrost, stating that a liner was not required only if the site was developed and operated to prevent permafrost degradation, adequate thermistor monitoring installed to detect any thawing, prohibited the disposal of oils, liquids from spill clean-up activities and any other wastes incompatible with freezeback, and finally, that after closure the waste would remain frozen (ADEC 1996). Thermistors are a thermally sensitive resistor whose primary function is to exhibit a change in electrical resistance with a change of temperature (Cormack 1987). If any of these stipulations were not met, then corrective actions including groundwater monitoring would be required. The first actual

freezeback landfill regulation package began in 2002, which included the same stipulations adopted in the 1996 state regulation for landfills located on permafrost (ADEC 2002). This set of regulations are still used today to govern the requirements for a successful freezeback landfill.

Alaska Solid Waste Regulation 18 AAC 60 permits the freezeback landfill design, which offers the benefits of not requiring the installation of an underlying liner, groundwater monitoring, or methane gas monitoring (ADEC 2017). By design the potential effects to the environment are minimized by keeping the waste frozen. The State of Alaska does stipulate the following criteria as a means of designation for a successful freezeback landfill:

- The landfill site is designed, developed, and operated to prevent permafrost degradation and ensures all of the waste will freeze with the permafrost and remain frozen.
- A sufficient number of temperature devices are installed and monitored to detect any thawing in the waste.
- Oils, liquids from spill cleanups, and waste that is incompatible with freezeback will not be placed in the landfill.
- After landfill closure, the waste will remain frozen (ADEC 2017).

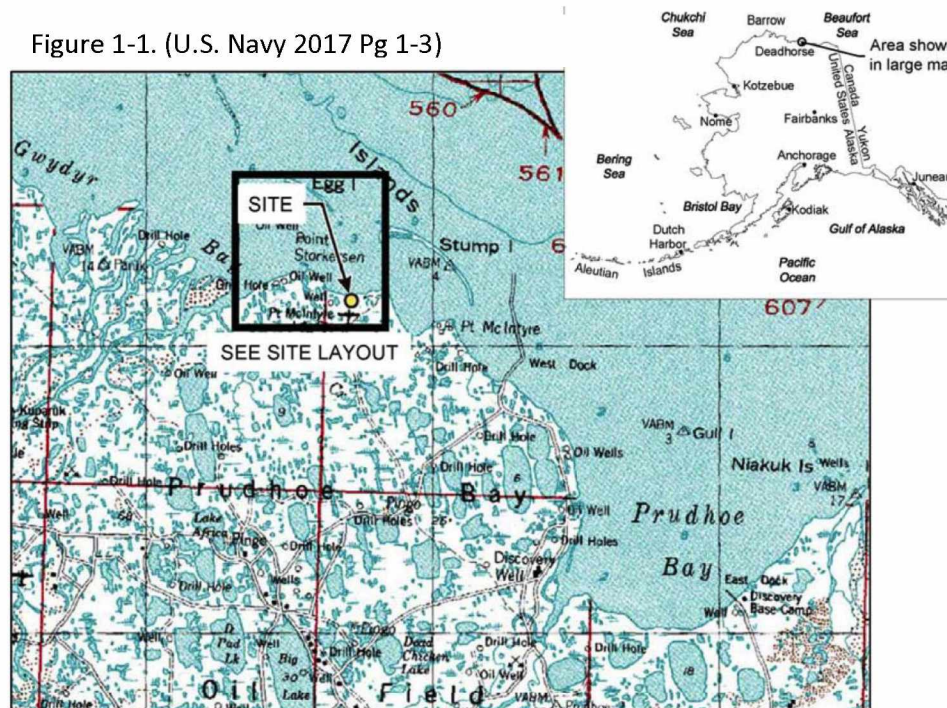
To protect the environment and demonstrate that the freezeback landfill is operating successfully the regulatory agency, Alaska Department of Environmental Conservation (ADEC), requires the landfill to be monitored for temperature and erosion during the landfill's active life and post-closure monitoring period.

Case Study #1 The Point McIntyre Freezeback Landfill

The first landfill to be discussed is owned by the United States Navy at Point McIntyre Alaska, approximately 15 miles northwest of Deadhorse on the coast of the Beaufort Sea as indicated in Figure 1-1. (U.S. Navy 2017). This is an areafill style landfill with waste being placed

on top of an existing airstrip. This type of landfill suited the environmental conditions and concerns due to the proximity of the ocean, potential storm surges, and local climate.

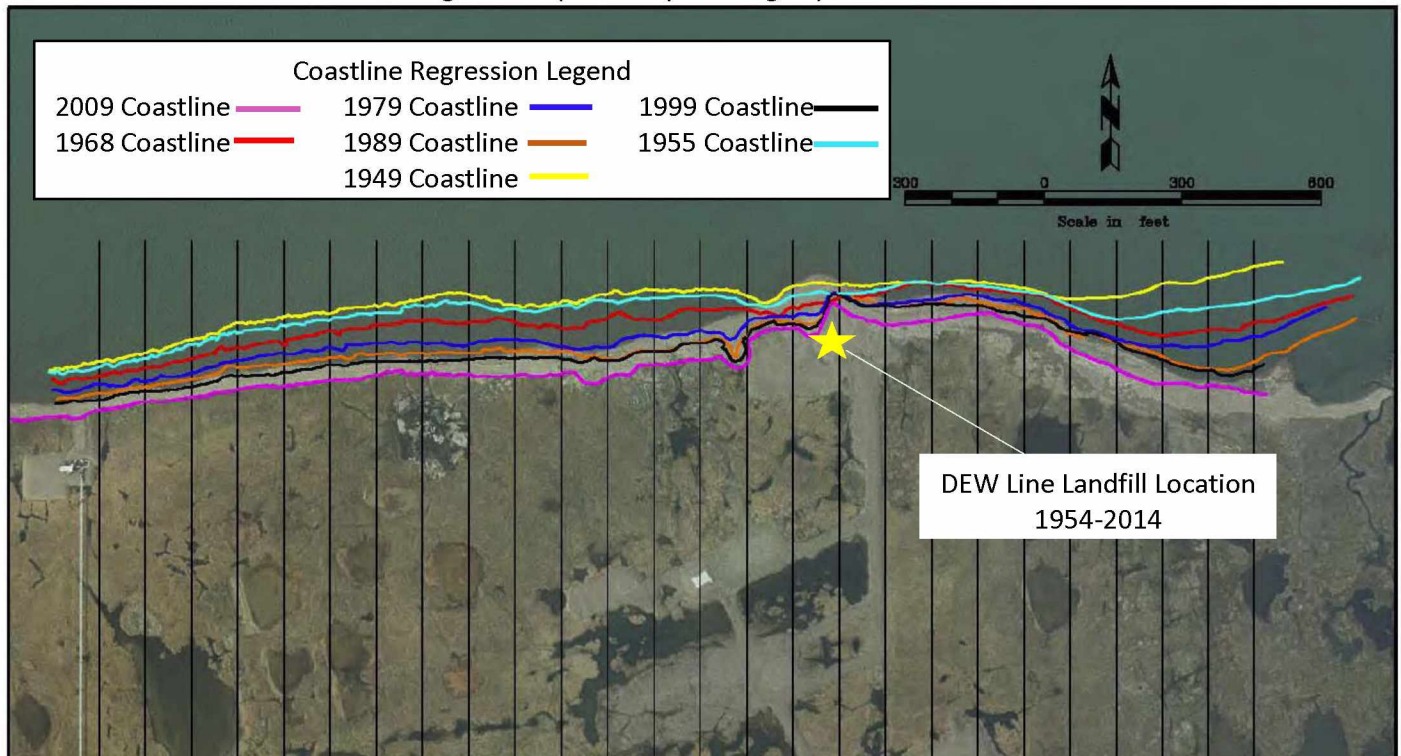
Figure 1-1. (U.S. Navy 2017 Pg 1-3)



This site was used as a distant early warning (DEW) line station operational from 1954 until 1958 (U.S. Navy 2017). In 1965 the U.S. Navy used the site as an Arctic research station until its closure in 1980 (U.S. Navy 2017). In 2004 the ADEC expressed concern regarding the eroding landfill along the coastline during the final closure and cleanup of the site. Due to climate change, the coastline near the site was eroding at an alarming rate, causing buried waste in the landfill to be exposed and washed into the Beaufort Sea. This development was further documented in the site inspection and report from 2004-2010 conducted by Coastal Frontiers Corporation (CFC) for the U.S. Navy, which also pointed out that the eroding landfill was increasingly susceptible to storm surges and thermal erosion of the coastline bluffs resulting in further degradation of the landfill (U.S. Navy 2010).

A study of the eroding coastline using historical aerial photos as seen in Figure 1-2 outlines the bluff regression from 1949 to 2009.

Figure 1-2. (U.S. Navy 2010 Pg 12)



Using the historical aerial photographs, CFC consultants identified an average erosion rate of 1 to 3 feet per year along the DEW Line landfill location. Based on this evaluation, CFC also calculated a 100 ft storm surge prediction for the surrounding topography. Using this data, the U.S. Navy proposed to move the landfill 1,100 feet inland and incorporate it into an existing airstrip (Figure 1-3). This is the highest elevation in the area at 12 feet above sea level, and outside of the predicted storm surge area (U.S. Navy 2017). The freezeback landfill design was utilized for this project to lower project costs while minimizing environmental impacts to the surrounding environment, given that the landfill cap should not be inundated by storm surges.

Figure 1-3. (Image Google Earth 9/4/2014 accessed 11/11/2018)

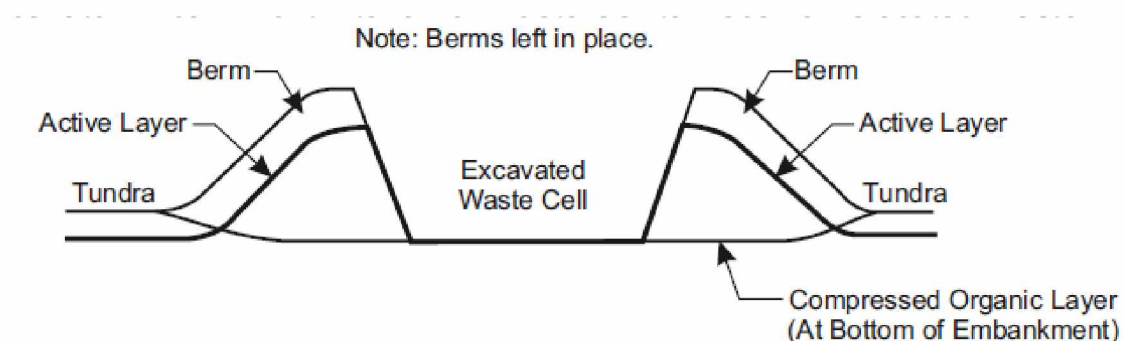


The new freezeback landfill situated in the airstrip at Point McIntyre was installed, filled, and capped in one year, 2013-2014. This time frame is consistent with case study #2 but still is a unique factor among freezeback landfills. Other permitted freezeback landfills accept waste on a regular basis throughout the life of the landfill, which is often a process of a few decades. Examples of these long life freezeback landfills include municipal solid waste facilities at Barrow, Kotzebue, and industrial sites along the pipeline corridor. Particular research interest in this landfill rests around the engineered final cap with daily thermistor data in evaluating the freezeback design.

The design chosen for the Point McIntyre freezeback landfill took advantage of the existing berms along the airstrip and excavated only down to the natural tundra elevation

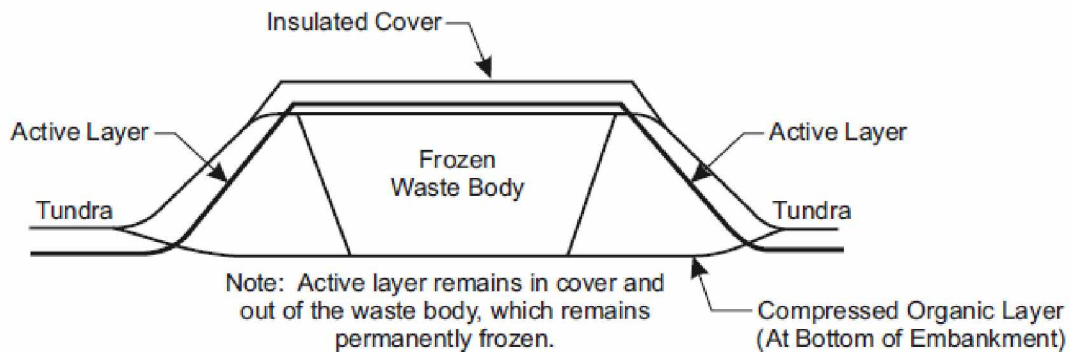
leaving the compressed organic layer in place. Approximately 6,650 cubic yards of nonhazardous debris was compacted and buried in the excavated waste cell within the airstrip as illustrated in Figure 1-4. The average daily temperatures were at or slightly above freezing in October dropping below freezing overnight therefore the waste which was stockpiled above ground is assumed to be at or close to 32 °F at time of disposal.

Figure 1-4. (U.S. Navy Freezeback Landfill Concept Schematic Figure B-1 2010)



Leaving the compressed organic layer or tundra mat in place may add a thermal protective layer to the underlying permafrost and prevent degradation. Removal or disturbance of the surface vegetation cover usually causes degradation of the underlying permafrost. In summer the tundra vegetation mat dries out and becomes an excellent insulator while in autumn snows wet the O and A horizons which then freeze producing a layer with relatively high thermal conductivity (Harris 1986). As with any freezeback landfill the final cover should uptake any active thaw layer allowing the underlying waste to remain frozen. The freezeback landfill design for Point McIntyre is unique in its engineering. It acts as an insulative cover protecting the waste from the active thaw layer, ambient air temperatures above freezing, albedo, and is designed to prevent ponding water from to settlement in the final cap as illustrated in Figure 1-5.

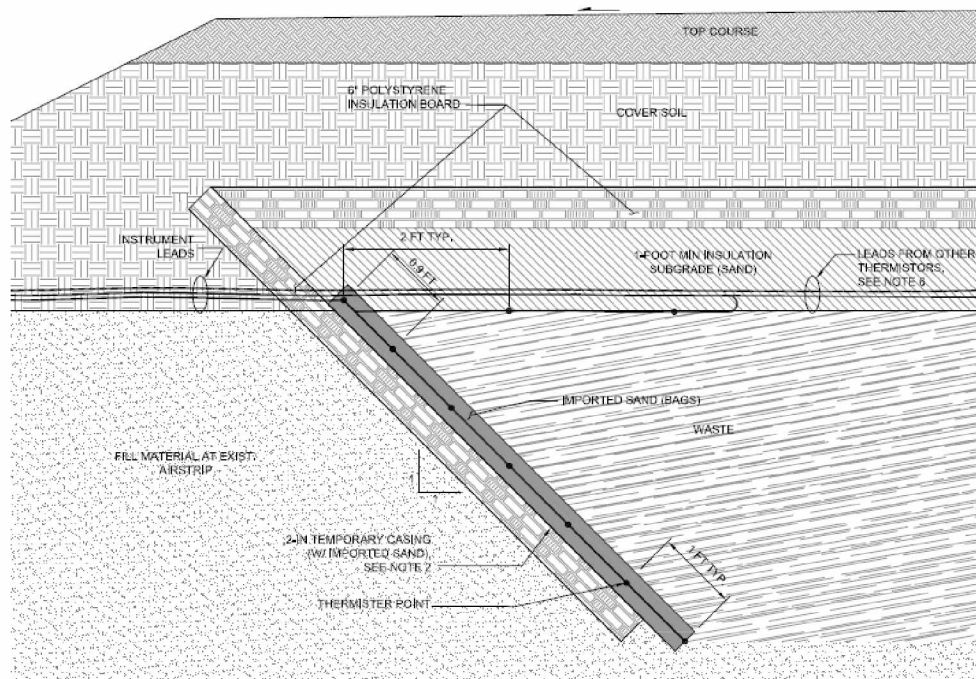
Figure 1-5. (U.S. Navy Freezeback Landfill Concept Schematic Figure B-1 2010)



Engineering so that the active thaw layer stays above the waste in a changing climate poses significant challenges. As previously mentioned, snow cover and ambient air temperature play a large role in active thaw layer, but the vegetative mat also plays a key role. When the protective cover is disrupted or removed, more heat reaches the surface of the ground, and the permafrost begins to thaw until a new thermal balance between heat input and cooling is established (McFadden 2001). Because the final cover on a landfill is a manmade structure within the natural topography, its influence on permafrost and effects on the active thaw layer should be considered separately from the surrounding environment, but designed to work in conjunction with the local climate. The surface temperature changes influence the temperature at each depth, and the influence arrives at each succeeding depth at progressively later times (McFadden 2001). These factors are why the final cover design on a freezeback landfill can critically affect the success or failure of the waste remaining frozen after the facility has closed. As illustrated in the cross-sectional view of the engineered cover at the Point McIntyre freezeback landfill in Figure 1-6, the final cover is a series of protective and insulative layers. The compacted waste is covered by a 1 ft layer of sand, then a 6in layer of polystyrene

insulation board, then 2 ft of soil, and finally a 6 in minimum layer of locally sourced soil, sloped over the landfill, to promote water runoff and vegetation growth. If R-value is a measure of how well an object, per unit of its exposed area, resists conductive flow of heat: the greater the R-value, the greater the resistance, and so the better the thermal insulating properties of the object, this cap design provides an R-value of 27 ($\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{h} / \text{BTU}$). Based on thermistor data collected at the Point McIntyre site an R-value of 27 ($\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{h} / \text{BTU}$) of the final cap inspires confidence of the long-term effectiveness of the freezeback landfill.

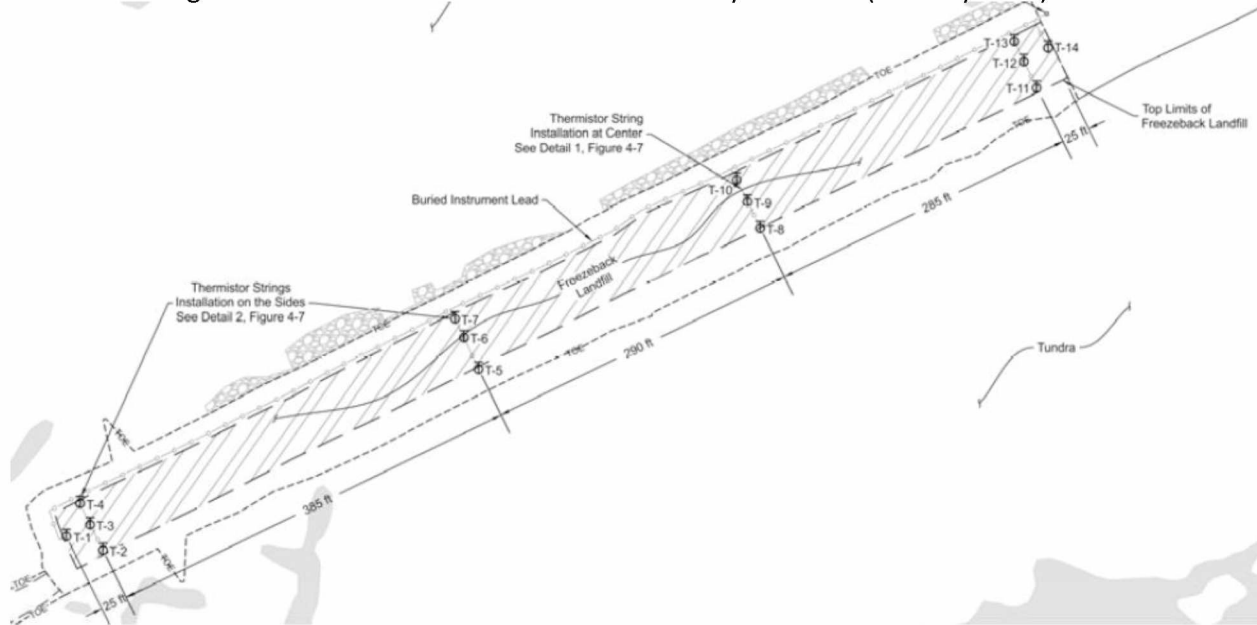
Figure 1-6. (US Navy Drawing No. C-9, 2010)



Building in permafrost regions requires an understanding of the nature of permafrost and the problems that its occurrence presents (McFadden 2001). A total of 14 thermistor strings with 10 thermistor points each and one thermistor string with three thermistor points were installed during the landfill cap construction to monitor waste temperature and the active thaw layer within the final cap (U.S. Navy 2018). The data captured by the thermistors is used

to evaluate the freezeback design and ensure the surrounding environment is not adversely affected by the waste. The Point McIntyre freezeback landfill will be monitored using temperature data from the thermistors, as shown in figure 1-7, as well as groundwater monitoring protocols for the next 30 years.

Figure 1-7. Thermistor Locations at Point McIntyre Landfill (US Navy 2018).



The thermistors are installed in 2 distinct patterns. Those that run along the side of the landfill, (T-1, T-2, T-4, T-5, T-7, T-8, T-10, T-11, T-13, and T-14) record data point temperatures 1-4 horizontally at the top of the waste. The data collection points #1 through #3 are spaced 2 ft apart horizontally and data collection point #4 is spaced 1 horizontal foot away from data point 3. Data collection points #5 through #10 follow the 1 to 1 slope along the sides of the waste. The thermistors are not collecting temperatures within the cap or active layer rather within the waste only. The thermistors that are placed in the middle of the landfill, (T-3, T-6, T-9, and T-12), have horizontal readings along the waste at data collection points #2, 3, 4, 5, and 6 with #7 through 10 collecting temperature data at 1 foot increments into the waste to a total

depth of 4ft. The thermistors are programmed to take daily temperatures although the time of day is not reported in public record. In evaluation of the collected thermistor data all recordings stayed below 32 ° F during the 2016 summer except for two locations which ranged from 32° to 32.5 ° F for three separate one-week durations. During the summer of 2017 three thermistors recorded temperatures from 32° to 33.5 ° F ranging from a few days to a week long period. Overall the 2016 to 2017 winter temperatures were several degrees colder than the 2015 to 2016 winter temperatures indicating that the landfill is continuing to cool (US Navy 2018). No signs of erosion, settling, or subsidence were recorded during site inspections in 2016 or 2017 indicating the landfill cover is performing as designed. The US Navy does identify that climate change in the future may have adverse effects on the Point McIntyre freezeback landfill although it currently meets the regulatory standards for a functional freezeback landfill. By not excavating into the vegetative mat or existing permafrost layer and incorporating the active layer on top of the waste the thaw depths do not reach the frozen waste. In addition to a final cover design, with an R-value of 27 ($\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{h} / \text{BTU}$), makes the freezeback landfill at Point McIntyre currently a success. However, there may be issues on the horizon for the Point McIntyre landfill. In photographs taken onsite the summer of 2018, it was evident that there is no vegetation growing on the landfill cover. Vegetation may provide additional thermal protection and control saturation of the soils. There is also an increase of ponded water along the sides of the landfill that may lead to permafrost thawing under the airstrip, resulting in subsidence in the landfill cover. Lakes can form due to altering the thermal regime and heat input will increase by removing the insulating organic soils or having shallow water (Fristoe 1990). The increased heat input will thaw into the permafrost, thawing ice rich soils and

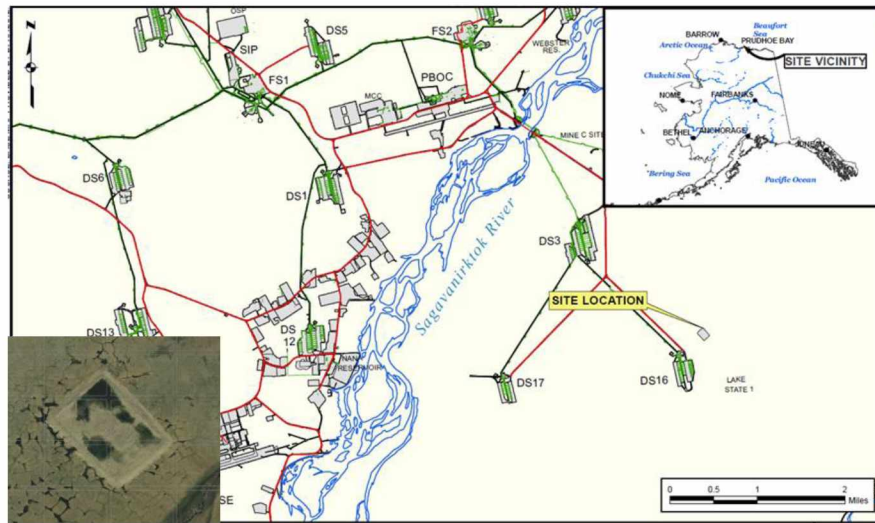
subsequent collapse of the soils, known as thermokarsting, creates a lake which further increases the heat input. This process repeats until thermal equilibrium is reached. What starts as a small depression may grow to a lake that will influence the integrity of the site (Fristoe 1990).

For all of its current success at reaching and maintaining freezeback status the Point McIntyre landfill is still potentially leaching heavy metals and volatile organic chemicals into the surrounding environment as noted in the annual groundwater monitoring report (US Navy 2019). If the Point McIntyre landfill is potentially impacting the surrounding environment, it poses the question if a freezeback landfill, when operating as designed, can completely minimize human and environmental health risks as theoretically proposed.

Case Study #2 The East Sagavanirktok Regional Disposal Facility (BPXA).

The second freezeback landfill to be evaluated in this research is BP Exploration (Alaska) Inc's, East Sagavanirktok Regional Disposal Facility (BPXA). To begin with some background information on this freezeback landfill and cover design, the BPXA landfill lies north of the Arctic circle near the coast of the Beaufort Sea and east of the Sagavanirktok River as seen in Figure 2-1 below (BP 2018). The local environment includes Arctic tundra vegetation, continuous permafrost, and a landscape inundated with polygons.

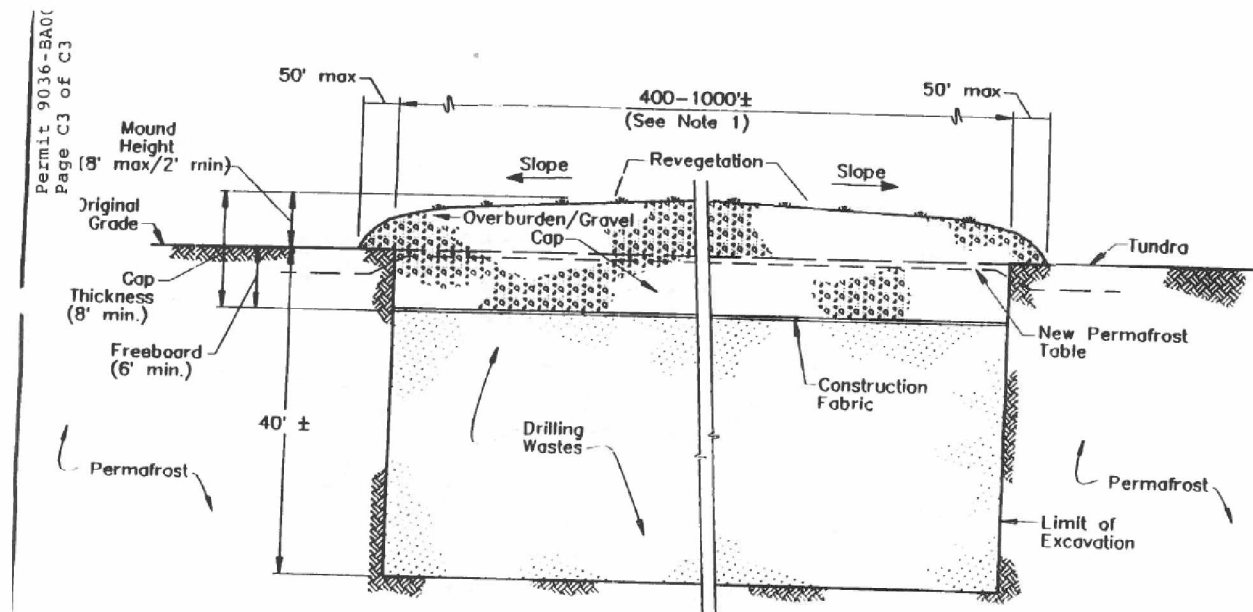
Figure 2-1. (BP 2018 Figure 1)



In 1992, ARCO Alaska Inc., constructed the BPXA facility, which was designed to function as a freezeback landfill, to dispose of nearby generated drilling wastes. The disposed debris consisted of both drilling wastes and other contaminated materials from a 2 million cubic yard stockpile (ADEC 1991). In drilling mud freezeback landfills the cover serves as a seal against escape of any unfrozen portion and as an insulation to contain the active layer and maintain the waste in the permafrost zone (Dyke 2001). The BPXA landfill differs from the Point McIntyre landfill as it operates as a trench and fill landfill rather than an above grade areafill. Tundra and mineral soil were excavated to approximately 40 feet below tundra grade, and drilling waste was placed within the excavated area to a pre-settlement elevation approximately 6 feet below tundra grade (BP 2015). After disposal, the waste was covered with approximately 6 feet of silty soil, followed by a minimum of 2 feet of gravel fill, and finally capped with 6 to 12 inches of tundra material – to a maximum (pre-settlement) height of approximately 11 feet above tundra grade all within a single year (BP 2015). Landfill caps are sloped so the deepest portion of the cap is in the middle and the toe edge will be the shallowest to promote water runoff from the

site. This short duration of construction, fill, and final closure is similar to the Point McIntyre freezeback landfill. Figure 2-2 depicts the final cover strategy for the BPXA landfill as approved in the 9036-BA008 landfill permit issued in 1991.

Figure 2-2. (ADEC 1991 Figure E-7)



Also, as required by their permit, the following criteria was required to be considered a successful freezeback landfill: 1) all waste is maintained at least six feet below the original ground level, and 2) and all waste is permanently frozen and remains at least two feet below the maximum depth of the active thaw zone (ADEC 1991). The exact depths of silt and gravel vary across the surface of the cap material due to subsidence both within the buried waste and the landfill cap itself. The subsidence combined with thaw instability and saturation rate differences between materials have created an undulating effect along the landfill cover's surface. This variance has resulted in water ponding on the landfill surface and exacerbated

challenges with meeting compliance with freezeback landfill criteria. The landfill was constructed within regulatory compliance at the time, however, this design has led to final cover subsidence, multiple feet in depth within the 11 ft thick final cover, and is potentially contributing to the upward trend in annual waste temperature readings. The active thaw layer is slowly descending deeper underground at the BPXA site and the permafrost temperatures are slowly rising in the region. In the future, the equilibrium between the active thaw layer and permafrost temperature may inhibit freezeback status. To ignore the permafrost invites the inevitable catastrophe that has so often resulted when construction proceeded without regard to the soil conditions of the site (McFadden 2001).

The two most important construction distinctions on permafrost soils are whether the permafrost soil is stable or non-stable when it thaws which is dependent on the amount of saturation contained within the frozen soil (McFadden 2001). Much of the subsidence in the BPXA freezeback landfill resulted from the saturated silty soil used within the cover and potentially in the waste stream itself resulting in a reduced R value ($\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{h} / \text{BTU}$). Initially using the standard value of soil's R-value of 1 ($\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{h} / \text{BTU}$) per 1ft of depth the originally installed final cap provided an R-value of 11 ($\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{h} / \text{BTU}$). However, with subsidence over the years the final cap R-value has been reduced to less than 8 in many areas.

Soil saturation levels play a key role in the overall stability when used in a landfill final cover. By definition saturation is when the volume of frozen water exactly fills the spaces between the grains of soil that are still in contact with one another (McFadden 2001). Saturation is the maximum amount of water the sample can hold in the pores between the contacting soil particles and is different for each soil type (McFadden 2001). In course-grained

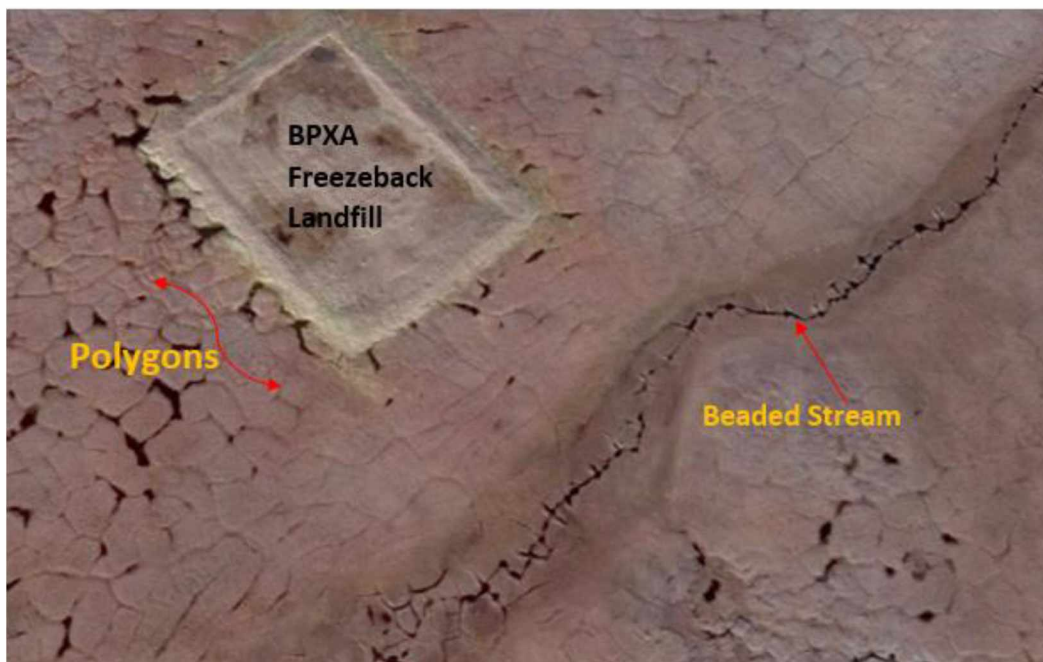
soils such as gravel the pores between particles make up a smaller volume than in finer grained soils on a per volume basis, and saturation can be near 5% of the dry weight, whereas in fine-grained silts, which are frequently found in cold regions, saturation is closer to 17% of the dry weight of the soil (McFadden 2001). The BPXA landfill cap has both gravel and silt which are on either end of the spectrum in saturation content. The silt for the landfill cover was utilized from the overburden from digging the trench. As such, the silty soil layers with different saturation levels were mixed together and then piled on top of the waste at closure. This potentially creates an unstable material for freeze thaw cycles. The gravel was placed on top of the potentially mixed silt layer. The waste itself is hypothetically not uniform, and as with all landfills, can suffer from subsidence as waste settles and degrades. The subsidence in the BPXA landfill cover can be from both the mixed silt used in the cover and also the thaw unstable waste.

Upon thawing, soil whose water content is at saturation or below will not change its volume or subside since the soil grains are in contact and is said to be thaw stable for construction without any additional elaborate measures (McFadden 2001). However in the BPXA landfill cap, the liquid water content of the silt can equal or exceed saturation so upon freezing the individual grains of silt will be separated by the expansion of the water as it crystallized into ice at different rates. When thaw happens within the silt soil layers the grains will condense until they settle together again causing subsidence. Subsidence is directly related to water content of the frozen materials (McFadden 2001). Thaw-induced subsidence typically results in ponding on the surface which is a condition that favors continued thaw (Dyke 2001).

The BPXA freezeback landfill is also more susceptible to albedo because the subsidence allows for ponding to occur resulting in a greater absorption of solar radiation.

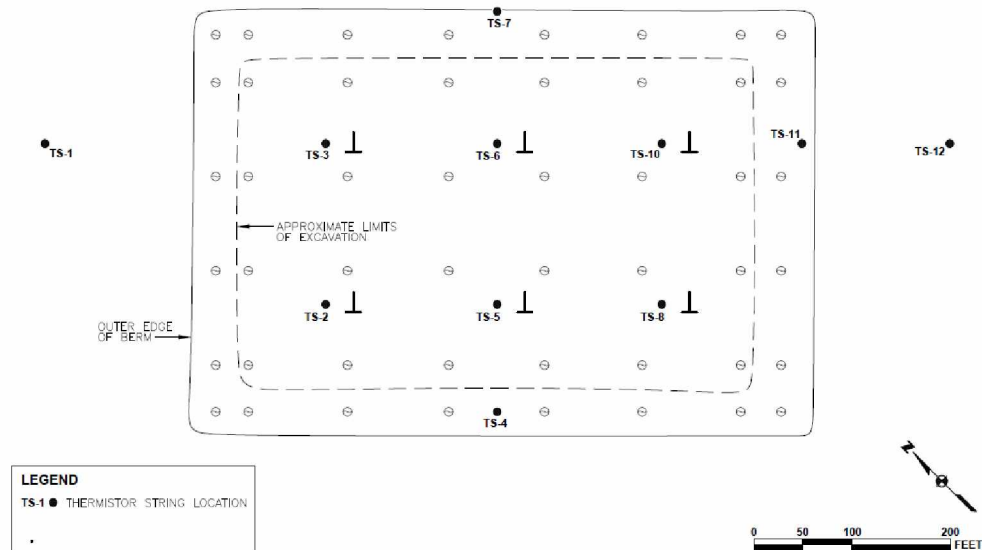
The BPXA cap consists of a mixture of silty and gravel rich soils with different saturation rates, creating a thaw unstable situation. The nearby beaded stream indicates, as identified in Figure 2-3, an area of massive ice. When a stream flows through permafrost containing massive ice forms, heat from the flowing water can melt ice wedges and lenses, which then causes subsidence. The result is a condition known as a beaded stream and is a distinctive indicator for massive ice in the area (McFadden 2001). Not only is the BPXA landfill final cover potentially under-engineered but it is also located in an area of unstable thaw within the natural environment.

Figure 2-3. (Google Earth image recorded 9/6/2014 and accessed 11/14/18)



As with the Point McIntyre freezeback landfill the BPXA landfill monitors thermal conditions using buried thermistors. The thermistor locations are outlined in Figure 2.4 below;

Figure 2.4. BPXA Thermistor Locations (BP 2016)



The landfill has been monitored since it closed in 1992, with a design failure temperature set at 30.5 °F at 24 ft. below grade surface (BP 2018). The thermistors record temperature at 2 ft increments from the ground surface to the bottom of buried waste and are reported elevation above mean sea level. Additional thermistors were installed in the surrounding tundra (thermistors 1 and 12) and side slopes of the landfill (thermistors 4, 7, and 11) to record active thaw layers outside the waste deposition area. Based on the 2018 monitoring report the temperature trend of the waste has a steady increase since 1992. However, based on temperature recordings in thermistors 1 and 12, the temperature of the surrounding tundra has also increased. As a stipulation of the permitting since 1992, only a single day of thermistor readings are required to be reported for the year. The reported readings are taken in September each year. The validity and usefulness of the single thermistor data point presented in public record is questionable in truly identifying what is occurring at the

BPXA site. The average annual temperature at 24 ft. below grade surface (bgs) in 1992 was 18.2 °F, however the average temperature at the same elevation in 2017 was 28.6° F representing a 10.4 °F increase (BP 2018). BP used natural logarithmic regression to predict that within 2 feet of the silt/waste interface, the waste will have an annual average temperature of 30.5 °F temperature by the year 2035 (BP 2018). Although BP presents the summary of their findings in an annual report the actual thermistor data presented in public documents is insufficient, by reporting a single day per year, to confirming the extent of success or failure of the landfill. The limited data appears insufficient to fully understand how the landfill cap is performing seasonally, the extent of the active layer, and to assess why the freezeback design may be failing in context with site specific data. The BPXA freezeback landfill will continue to struggle with design issues by disruption into the underlying permafrost, removing the vegetative mat, final cap materials made from thaw unstable soils and different saturation rates, disposal of thaw unstable wastes, and a site location with indicators of underlying massive ice.

The BPXA freezeback landfill is not a unique situation. Over 100 similar landfill sites are scattered within Canada's Mackenzie River delta region commonly referred to as "sumps." These sumps are tennis court sized holes excavated 3-4 meters deep into the permafrost and are used as a means to dispose of drilling mud wastes generated from oil and gas exploration (Pelley 2005). It is reported that half the sumps constructed in the 1970s have melted the surrounding permafrost and have a collapsing sump cover some in part to the use of potassium chloride within the drilling mud as an antifreeze agent (Pelley 2005). Freeze-thaw cycles boost the concentration of the potassium chloride at the edge of the sumps and thawing lenses of ice in the permafrost increase the hydraulic conductivity of soil which increase migration offsite. In

a preliminary assessment of five sumps showed that the potassium chloride is migrating hundreds of meters away from the pit suggesting that permafrost alone cannot contain contamination (Dyke 2001). Inadequate engineering controls and failing cover strategies of freezeback landfills in the Arctic regions of the globe will need to be addressed to control pollution leaching offsite from these facilities into the surrounding environment in the immediate future.

Case Study #3 Alyeska Class III Camp Landfill 117-1B

The third landfill in this research is the permitted Alyeska 117-1B Class III Camp landfill and under the authorized operations plan, operates as a freeze back landfill. The Class III Camp designation of the landfill limits the disposal to less than one ton of incinerator ash from municipal solid waste, as well as ash from varying waste streams, inert waste, and construction and demolition debris. As a stipulation of the permit, Alyeska must also conduct thermal monitoring (ADEC 2017). It has been a permitted landfill facility since 1979 although intermittently accepting wastes throughout its lifespan. The 1979 permit outlines much of the same allowable waste streams as the current permit issued in 2016 as ash, combustion residues, and construction and demolition debris (ADEC 1979). These waste streams are considered the bulk of what is buried in the 117-1B landfill when evaluating potential final cover strategies for this facility. This landfill operates as a trench and fill style landfill similar to the BPXA landfill, however, 117-1B has accepted waste into multiple trenches throughout its lifespan rather than a single large disposal event. The facility is located on a ridge line about one mile south of the Dalton Highway at Milepost 285 as shown in Figure 3-1.

Figure 3-1. Google Earth Image recorded 7/11/2008 accessed 8/1/2019



The current landfill design (as shown in Figure 3-2) allows for 21 cells of varying size on a 110-acre site. Digital imagery and site report photos suggest the landfill has been stripped of native vegetation since 2001. The 117-1B landfill has struggled handling the water that appears in open waste trenches. In 1992, it was reported that 165,000 gallons of water were pumped out of cell #20 (Alyeska Pipeline Service 1996). The cause as documented in numerous public records from Alyeska, was identified as melting of supra-permafrost melt water flowing from the pit walls and bottom into the pit where it collects¹. Research published by Brad Fristoe in 1990 states that waste placed in below grade reserve pits have been documented as thawed for two years after closeout due to stored heat and latent heat of freezing. An excavated pit forms a bowl in the permafrost that can fill with sheetflow of surface meltwaters (Fristoe 1990). The amount of groundwater flowing above and within the permafrost can indicate a potential issue that may need to be evaluated in the final cover strategy to reach a successful freezeback at the 117-1B landfill site. This amount of groundwater flowing through the waste, seasonally freezing, and then melting in the spring may produce leachate that, under certain conditions,

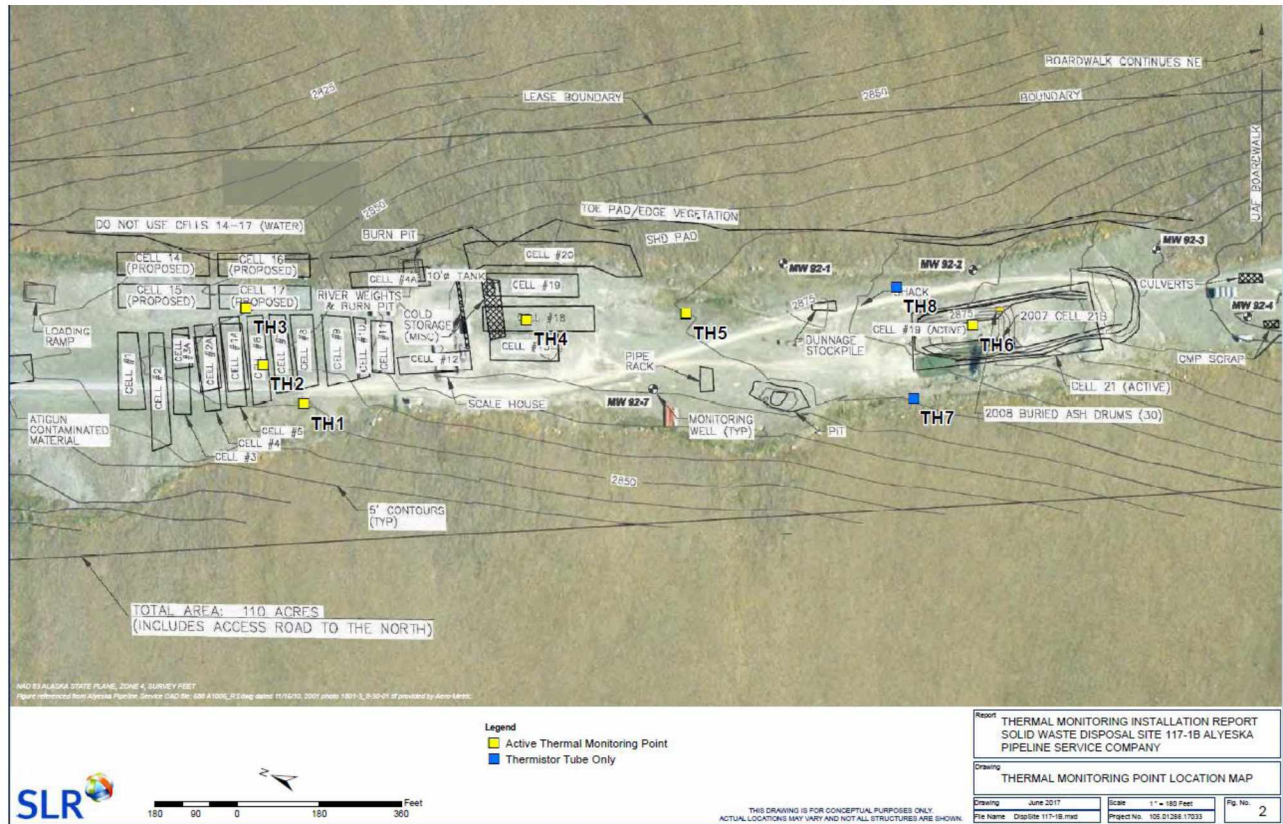
¹ See Appendix A for Alyeska Pipeline Service Company comments on Case Study #3

could transport² contaminants off site. This potential risk makes a successful freezeback strategy all the more important at this site.

In 2006, a different operation scheme was utilized where the pit would be opened up in the active cell once per year. Once opened, waste would be disposed of during that single annual event and then intermediate cover would be added to prevent thawing of the existing waste and permafrost. No ponding was reported in the 2007 annual report for the 117-1B landfill; the annual disposal event worked well, and it was anticipated that it would be the preferred method of managing the disposal site (Alyeska Pipeline Service 2007). In the 2007 annual disposal event, 92 drums of incinerator ash were placed in landfill near cell #20 (Alyeska Pipeline Service 2007). The landfill has not accepted any waste since 2007 (Alyeska Pipeline Service 2009). The landfill may still be used in the future to accept construction and demolition debris from legacy structures and equipment at pump stations 3 and 4 (Alyeska Pipeline Service 2013).

² See Appendix A for Alyeska Pipeline Services Company comments on Case Study #3

Figure 3-2. (Alyeska 2017) 117-1B Landfill Site Plan



Thermistors (as indicated on Figure 3-2) were required to be installed at the 117-1B landfill in 2017 to evaluate maximum thaw depth and to determine if waste remains frozen throughout the year (Alyeska 2017). A key piece of information is missing to achieve the goal of the thermistors. Of the 8 boreholes drilled at the site, 6 received thermistor strings, (TH1 through TH 6) each with varying depths of 13 to 26 feet in depth below grade surface; however, the depth to waste in any of the closed cells remains undocumented in public records³. In order to truly asses that the landfill is reaching and maintaining freezeback status or at least identifying how far the active layer extends into the waste, the depth to waste needs to be

³ See Appendix A for comments from Alyeska Pipeline Service Company on Case Study #3

evaluated for each waste cell in the landfill. In order to maintain freezeback, the waste needs to sit below a stabilized active thaw layer with an adequate buffer between the two.

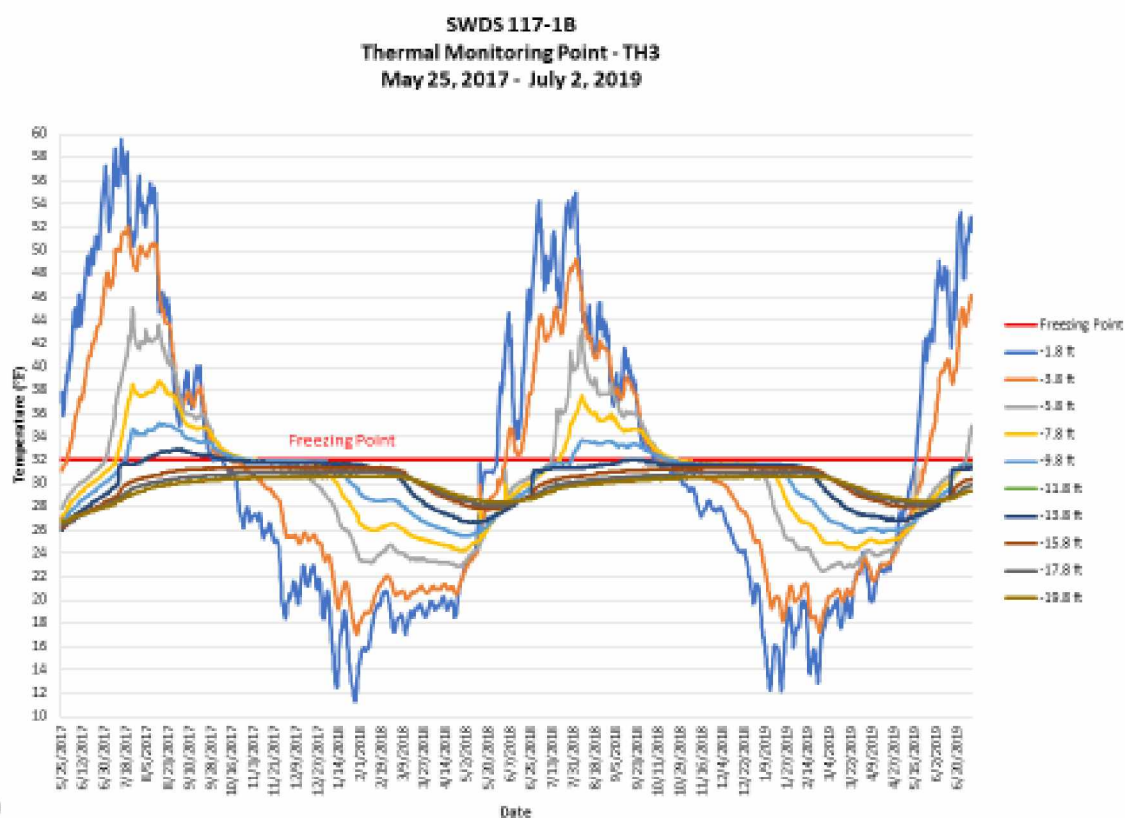
It is unfortunate that the depth to waste was not recorded in the drill logs from the thermistor bore holes while installing the thermistors in April 2017 (Alyeska Pipeline Services 2017). However, the logs did provide some insight on soil types, generally consisting of gravel and boulders from 0-15ft and sand, gravel, and silt at 15-25 feet bgs. The bore logs do align with the physical description of the area as Cretaceous and Jurassic in age sandstone and conglomerate with some shale with the bedrock being overlain with 1-5 feet of silts, sands, and gravel as described in the 2006 site narrative of the 117-1B landfill permit renewal application. The only inconsistency reported in the drill logs was at drill site for thermistor 6. A hydrocarbon smell was reported from the sample return from 5-15 feet below grade surface⁴. This is likely the disposal location of the 40,500 burlap bags of petroleum contaminated soil that was disposed in the landfill in 1980 with approval from the ADEC. The material may have been generated from a spill clean-up activity in Atigun Pass in 1979. In figure 3.2 the Atigun pass material is noted to have been disposed of near thermistor TH2 in cell #3 however no notes of hydrocarbons were reported in the bore logs (Alyeska Pipeline Services 2017). The hydrocarbon smell may indicate other petroleum contaminated materials at the site.

The 117-1B landfill is a representative Class III Camp landfill in the types of waste disposed however it is one of the only camp landfills trying to operate and close out as a freezeback. In evaluating the thermistor data from TH1 through TH6, the 117-1B data set

⁴ See Appendix A for Alyeska Pipeline Service Company comments on Case Study #3

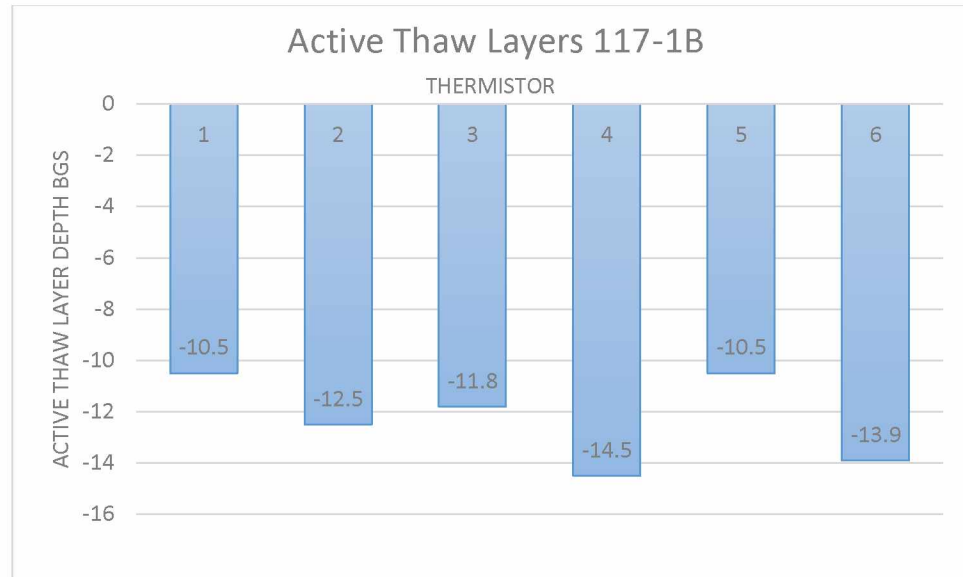
represents the most complete set of temperature data of all 3 case studies. Temperatures were recorded at 2ft increments at 0400 and 1600 daily from May 2017 extending beyond January 2019. It is consistent with the Point McIntyre data in that the thermistor beads closest to the surface are warmest in the summer months and provide the lowest temperatures in the winter months as indicated in the 117-1B thermistor plot in Figure 3.3 below.

Figure 3.3. (Alyeska 2019) Thermistor Plot Data from TH3



The 117-1B final cover design should encase any active layer on site, leaving the underlying waste frozen. The graph in Figure 3.4 outlines the depths that reach 32 °F according to the thermistor data collected on site.

Figure 3.4. (Data extrapolated from Alyeska 2019) Active Thaw Layers



Understanding where the current active layers are within the landfill is important in regards to the depth to frozen waste bgs. The knowledge of the active thaw layers will identify if waste is currently located within the active layer and is susceptible to an annual freeze thaw cycle. The active layer depth varies at each thermistor location. The active layer depth is important information but in analyzing the twice per day temperature recordings, there may be other perhaps useful information that can be used in engineering a successful landfill cover for the 117-1B site.

The two-foot increment thermistor reading directly below the active layer is often colder than its underlying thermistor, which reads at 4 feet below the active layer. This temperature anomaly is true for all 6 of the thermistor locations at some point during the year but most often in March and April. An example of this anomaly includes TH5 where the active

layer sits at -10.5 bgs, the -12.5 layer is colder than the -14.5 bgs layer in the months of May, June, and the latter half of April in 2019. This result may suggest that 2 ft below the active layer gets the most amount of cooling from the seasonal cold winter atmospheric temperatures as well as the steady cooling from the underlying permafrost. The -16.5 bgs layer shows little variation from the bottom thermistor bead at -20.5 bgs. This result may suggest that the -20.5 bgs layer represents the constant permafrost temperature range of 29.61° to 33.32 °F. This result may further indicate that for a higher level of success the landfill cover should be engineered to protect not the cold adjacent layer next to the active layer but engineer to protect the proceeding 4 to 6 ft in depth where the permafrost is maintaining a temperature range without influence from the cooling winter air temperatures pushing down into the ground at the 117-1B landfill site. Currently, below the active layer the permanently frozen layers are near 32 °F for most of the year allowing for a large window of zero curtain effect, or where the phase transition of water to ice is slowed down due to latent heat release. This situation allows the release of latent heat preventing the rapid cooling of soil temperatures at a uniform rate. This negative influence on a freezeback landfill could be minimized by achieving and maintaining slightly lower temperatures near the waste depth.

Recommendations

Given the evaluation of what works with the final cover at the Point McIntyre freezeback landfill, aspects that are leading to a failure of the BPXA landfill, and research on permafrost environments, the following are options for further research when considering a

final cover design for the 117-1B landfill. These options are using topographical influences to minimize snow cover, using segregated compaction layers of similar saturation rates within the final cover, creating a vegetative cover that helps protect the freezing temperatures of the underlying waste, the use of engineered modeling or alternative covers, and, since this is a multiuse site, minimizing activities in the future that will increase the albedo of the land surface. These concepts are not new as Fristoe stated in 1990, “factors that can affect sites are wind exposure, sun exposure, distance to the ocean or Brooks Range, cover material used, soil moisture content, and susceptibility to snow drifting.”

Snow cover can play a crucial role in the success of the freezeback landfill at 117-1B. It is well documented that snow acts as an insulator from the colder ambient air temperatures in the winter resulting in a warmer ground surface. The longer the ground surface can stay snow free in the late fall and early winter months, the sooner the active layer will begin to freeze. The snow may also help protect the balance of the underlying permafrost to keep the waste frozen.

In a study published in 2019 by Yi et al., it was determined that in Arctic Alaska, the timing of early snow accumulation was the primary factor affecting the freezing process of the top soils, while thawing in the active layer is more closely related to the length of zero-curtain (time that soils maintain a 0°C temperature) period in deeper soils. Analysis of data collected by in situ conditions, radar, and modeling results showed that early snow accumulation is the main control on the soil freezing for the upper 0.4 meter active layer. Earlier snow onset may enhance thermal buffering of cold surface temperatures and promote soil warming in colder climate zones in the Arctic region of Alaska and a shorter snow season may cool the soil in colder areas due to less insulation from cold atmospheric temperatures (Yi 2019). The study

also indicated that with an earlier snow onset, a longer zero-curtain period occurs which delays freezing and has a greater impact on soils deeper than 0.5 meters bgs. By controlling the timing and accumulation of snow cover over the landfill final cover, the results will have the greatest influence on the 0.4 meters bgs. It may also to some extent, shorten the time the active layer below 0.5 meters bgs will remain in the zero-curtain time period allowing latent heat processes deeper into underlying soils.

The insulating effect of deep snow tends to prevent the formation of permafrost (McGee et al. 2002), but a long term solution could be adding earthen berms along the upwind side of the ridge along the landfill that act as a snow break much like a snow fence. The berms may result in more snow free days in the colder temperatures as well as a shallower insulative snow cover. An inexpensive way to test this method would be to install a temporary snow fence while the thermistors are actively recording temperatures. Measuring the snow depth on site throughout the winter along with the temperature data collected may indicate a positive correlation in the response in the active layer depth, temperature, and freeze thaw cycle in relation to the snow cover duration and accumulation. Although neither the Point McIntyre or the BPXA landfill control timing or accumulation of snow cover, it may be needed in the future to maintain freezeback status.

The next option for further evaluation is to use segregated layers of materials within the final cover, preferably with lower saturation rates. In freezeback landfills the types of soil and moisture content are critical to minimizing the final cover thickness and obtaining thermal balance in materials high in moisture content and low in silt content to achieve freezeback (McGee et al. 2002). In a study of alternative caps for Arctic landfills a freezeback landfill cover

design was evaluated for the 18 acre Barrow landfill and found to be less cost effective than a synthetic liner due to the local material source consisting of saturated silty soils (Hinds 2002).

Using materials with the same level of expansion and contraction rate within the freeze-thaw cycle may minimize a whole host of issues that can present in the final cover over time. During the unidirectional freezing process, the external water migrates to the interior of the soils and a great quantity of segregated ice is formed in the frozen area accompanied by frost heave (Xain et al. 2019). The influence of freeze-thaw cycles on physical and mechanical properties of soil is reflected on the variation of microstructure of the soil (Xain et al. 2019). Using differing soil types mixed together and compacted as a final cover may result in settling with compounding issues of ponding and loss of R-value in the final cover. Also as indicated within this research a final cover design that has an R-value of less than 11 ($\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{h}/\text{BTU}$) within the soils has proven to be inadequate to maintain an active thaw layer above the waste. A minimum R-value of 27 ($\text{ft}^2 \cdot ^\circ\text{F} \cdot \text{h}/\text{BTU}$) of the final cover design has been shown to maintain below freezing temperature in the buried waste with a slow decrease in annual average temperature. Using distinct compacted layers of soil types as utilized in the Point McIntyre landfill cover may lead to a successful final cover strategy for the 117-1B freezeback landfill.

The Point McIntyre landfill also found that in their design modeling the most effective placement of extra gravel for increased cover thermal performance is directly below the insulation and directly above the waste body (US Navy 2010). They stated “inch for inch, increased gravel thickness is most effective when placed in the gravel leveling course below the insulation, not in the gravel cover above the insulation” (US Navy 2010). In the event that Alyeska decides to use an insulate layer such as foam boards adding additional cover material

directly over the waste, then adding the foam insulation may be a more successful strategy.

Also to note from the US Navy modeling of freezeback landfill covers they recommended using non frost susceptible gravels and sands such as materials with fines content below six percent, passing the No. 200 sieve (US Navy 2010).

A vegetative cover can play an important role in minimizing the depth of the active layer and decrease the saturation rate of the underlying soils. The control of vegetation above the permafrost layer may imply a positive feedback: vegetation controls soil temperature, which affects the stability of the permafrost layer and conditions suitable for plant establishment and growth (Runyan 2012). Saturation of soils can have large influence on underlying permafrost. Vegetation cover played an important role in protecting or driving permafrost changes by varying the water-thermal coupling cycle; consequently, differences in vegetation cover in the active layer of soils cause different thaw-freeze cycles and thermal regime (Genxu 2012).

The vegetation can also reflect and absorb solar energy that would otherwise be absorbed by the ground surface. It can affect snow distribution across the site that can promote longer freezing temperatures below the ground surface. In a 2012 study by Genxu et al. found that changes in vegetation cover influenced the energy flux on the ground surface and the surface soil properties. Consequently, the changes in the surface energy flux and the differences of air-soil temperature altered the active layer soil temperature, water distribution, and dynamics. The water and temperature dynamics of the active layer soil changed significantly with variations in vegetation cover.

A vegetative cover plays a key role in creating balance in the thermal regime of underlying permafrost and as such, is a regulatory requirement in the closure process of a freezeback landfill. Evaluating a variety of native vegetation that would help maintain the balance in temperature of the underlying frozen waste and permafrost is encouraged rather than using a general mix of native grasses when revegetating the final landfill cover at site 117-1B. Shrub vegetation may continue to migrate north as the climate changes occurs which can affect the landfill cover. Grasses allow for less snow to accumulate than shrubs in a windswept tundra environment. A few tens of centimeters of snow can raise ground surface mean annual temperatures by several degrees (Dyke 2001) so the types of vegetation can work for or against the freezeback design. As the site has been stripped of vegetation for decades and the growing season is short in the arctic environment it may take a significant amount of time to get adequate vegetation established on site and see its contribution to the overall thermal regime.

Modeling may be useful in designing a final cover strategy. The Berggren and Stephen equations are established engineering model equations to estimate the depth on a soil profile where the 32° isotherm lies at maximum thaw (Cormack 1987). They use a coefficient which considers the effects of temperature changes within the soil mass, average thermal conductivity, air thaw index, empirical constant relating air and surface thawing indexes, and latent heat to calculate the depth to thaw. Another engineering strategy that could be utilized is an air convection embankment (ACE). This technique uses poorly-graded material such as gravel or rock with a low fines content, placed usually on road embankments, but in this case as a final landfill cover addition. These types of materials allow for natural convection of the pore air to occur during winter months in reaction to an unstable density stratification of the pore air

(Goering 1998). In winter, the colder pore air in the upper layer of the material will descend due to its greater density, while warm pore air from the base rises (Goering 1998). The ACE creates a pattern of convection cells that transport heat from the base layer materials to the surface in winter. In summer the ACE cover creates a density stable stratification where warm air is layered over the cold air preventing cooling loss by averting convection (Goering 1998). An ACE may effectively trap colder temperatures in the landfill cap, decreasing the range of the active thaw layer and promote freezeback.

Once the landfill site is closed the final recommendation is to minimize activities that will disturb the temperature balance after freezeback is achieved and maintained. The active layer can be very fragile. When the active layer is removed or disturbed, permafrost is no longer insulated from the summer heat and within 2 years of disturbance, settlement from thawing can be 10-25 percent of the original active layer depth depending on actual water content and soil type (McGee et al. 2002). Since the 117-1B landfill is located in an area with open access to multiple use activities, it will be imperative that some site control be established. When a disturbance is imposed on the system such as the removal of vegetation it may cause an abrupt and highly irreversible shift from a stable permafrost state to an unstable one (Runyan 2012). As the 117-1B site is currently used as a laydown yard, in the future, these practices and any other activities, need to be evaluated for potential thermal destabilization effects on the landfill or impacts to the final cover.

Conclusion

Freezeback landfills are an exciting concept but a challenging in execution. There is not a single variable that leads to the success of a freezeback landfills but multiple variables in balance with each other that allow for freezeback to occur. Freezeback landfills should be engineered to the site-specific environment at the initial design stage for a better chance of success rather than following the generalized regulatory requirements. The changing climate may eventually tip the scales against freezeback landfills but hopefully a new engineering design that is successful in the new climate regime will take their place.

References

Alaska Department of Environmental Conservation (ADEC). 2017. *18 AAC 60 Alaska Solid Waste Regulations*. Web. <http://dec.alaska.gov/commish/regulations.aspx>. 10/16/2018.

Alaska Department of Environmental Conservation (ADEC). 2002. *18 AAC 60 Alaska Solid Waste Regulations*. Accessed via public records request 9/15/19

Alaska Department of Environmental Conservation (ADEC). 1996. *18 AAC 60 Alaska Solid Waste Regulations*. Accessed via public records request 9/15/19

Alaska Department of Environmental Conservation (ADEC). 1987. *18 AAC 60 Alaska Solid Waste Regulations*. Accessed via public records request 9/15/19

Alaska Department of Environmental Conservation (ADEC). 1973. *18 AAC 60 Alaska Solid Waste Regulations*. Accessed via public records request 9/15/19

Alaska Department of Environmental Conservation (ADEC). 1991. *ADEC Issued Permit 9036-BA008 to ARCO Alaska, Inc. for the East Sag Regional Solid Waste Disposal Facility*. 11 April 1991.

Alyeska Pipeline Service Company. 2019. *Thermal Monitoring Report Alyeska Solid Waste Disposal Site 117-1B, May 25, 2017 through March 25, 2019*. Prepared by SLR International Corporation for Alyeska Pipeline Service Company. March.

Alyeska Pipeline Service Company. 2017. *Thermal Monitoring Report Alyeska Solid Waste Disposal Site 117-1B, May 25, 2017 through December 31, 2017*. Prepared by SLR International Corporation for Alyeska Pipeline Service Company. January.

Alyeska Pipeline Service Company. 2013. Linda Edwards letter to Neil Lehner, ADEC on December 27, 2013. *Annual update of Alyeska Solid waste Disposal Sites 117-1B*. On file with the ADEC.

Alyeska Pipeline Service Company. 2009. Linda Edwards letter to Ken Spiers, ADEC on December 22, 2009. *Annual update of Alyeska Solid waste Disposal Sites 117-1B*. On file with the ADEC.

Alyeska Pipeline Service Company. 2007. Linda Edwards letter to Ken Spiers, ADEC on December 20, 2007. *Annual Update of Alyeska Solid Waste Site 117-1B*. On file with the ADEC.

Alyeska Pipeline Service Company. 2006. *Class III Camp Landfill Renewal* application submitted by Alyeska Pipeline Services Company to ADEC June 28, 2006. On file with the ADEC.

Alyeska Pipeline Service Company. 1996. Brian Seward letter to Laura Ogar, ADEC on November 25, 1996. *Response to October 28, 1996 letter concerning TAPS Solid Waste Disposal Site 117-1B*. On file with the ADEC.

BP Exploration (Alaska) Inc. 2018. *2018 Solid Waste Facility Compliance Monitoring, East Sag Regional Disposal Facility*. Prepared by ERM Alaska, Inc for BP Exploration (Alaska) Inc. November.

BP Exploration (Alaska) Inc. 2018. *2017 Solid Waste Facility Compliance Monitoring, East Sag Regional Disposal Facility*. Prepared by ERM Alaska, Inc for BP Exploration (Alaska) Inc. January.

BP Exploration (Alaska) Inc. 2016. *2016 Solid Waste Facility Compliance Monitoring, East Sag Regional Disposal Facility*. Prepared by ERM Alaska, Inc for BP Exploration (Alaska) Inc. November.

BP Exploration (Alaska) Inc. 2015. *2015 Solid Waste Facility Compliance Monitoring, East Sag Regional Disposal Facility*. Prepared by ERM Alaska, Inc for BP Exploration (Alaska) Inc. November.

Cormack R. *Thermal Modeling for Freezeback Disposal of Drilling Wastes on Alaska's North Slope*. <http://search.ebscohost.com/login.aspx?direct=true&db=cat07106a&AN=uaf.4068084&site=eds-live>. Accessed October 15, 2019.

Dyke LD. *Contaminant Migration through the Permafrost Active Layer, Mackenzie Delta Area, Northwest Territories, Canada.*; 2001. <http://search.ebscohost.com/login.aspx?direct=true&db=cat07106a&AN=uaf.4206951&site=eds-live>. Accessed October 15, 2019.

Fristoe, Brad. 1990. *Drilling Waste Management for Alaska's North Slope*. Proceedings of the First International Symposium on Oil and Gas Exploration and Production Waste Management Practices. September 10-13, 1990 New Orleans, Louisiana.

Genxu, W., Guangsheng, L., Chunjie, L., & Yan, Y. (2012). The variability of soil thermal and hydrological dynamics with vegetation cover in a permafrost region. *Agricultural and Forest Meteorology*, 162-163, 44-57.

doi:<http://dx.doi.org.proxy.library.uaf.edu/10.1016/j.agrformet.2012.04.006>

Goering, Douglas J. 1998. *Experimental Investigation of Air Convection Embankments for Permafrost-Resistant Roadway Design*. PERMAFROST-Seventh International Conference. Yellowknife Canada, Collection Nordicana No 55.

Harris, Stuart. 1986. *The Permafrost Environment*. S.A.H. Books Ltd. Great Britain

Hinds C, LeMay J, Stricklan K. Evaluating Capping Alternatives for an Arctic Landfill. *Cold Regions Engineering*. January 2002:897.

<http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=112787830&site=eds-live>. Accessed October 15, 2019

Magee GL, Rice WJ. 2002. Rethinking Landfill Development and Operation in Permafrost Regions. *Cold Regions Engineering*. January 2002:910.

<http://search.ebscohost.com/login.aspx?direct=true&db=edb&AN=112787831&site=eds-live>. Accessed September 16, 2019

McFadden Terry, 2001. *Design Manual for Stabilizing Foundations on Permafrost*. Permafrost Technology Foundation. Web. 10/26/18

<http://www.cchrc.org/sites/default/files/docs/DesignManualforStabilizingFoundationsonPermafrost.pdf>

Pelley, J. (2005). Are permafrost landfills safe for used drilling mud? *Environmental Science & Technology*, 39(11) Retrieved from <https://search-proquest-com.proxy.library.uaf.edu/docview/230146432?accountid=14470>

Romanovsky, V.E., W.I. Cable, A.L. Kholodov, S.S. Marchenko, S.K. Panda, N.I. Shiklomanov, and D.A. Walker. 2014. *Changes in Permafrost and Active-Layer Thickness due to Climate in the Prudhoe Bay Region and North Slope, AK*. Poster presentation, Arctic change 2014 Conference. Web. 10/14/18

http://www.geobotany.uaf.edu/library/posters/Romanovsky2014_OttawaAC2014_pos20141205.pdf

Runyan, C. W., & D'Odorico, P. (2012). Ecohydrological feedbacks between permafrost and vegetation dynamics. *Advances in Water Resources*, 49, 1-12.

doi:<http://dx.doi.org.proxy.library.uaf.edu/10.1016/j.advwatres.2012.07.016>

Torre Jorgenson, Kenji Yoshikawa, Mikhail Kanevskiy, and Yuri Shur. 2008. *Permafrost Characteristics of Alaska*. University of Alaska Fairbanks, Institute of Northern Engineering, Fairbanks, Alaska. Web. 11/1/2018

http://permafrost.gi.alaska.edu/sites/default/files/AlaskaPermafrostMap_Front_Dec2008_Jorgenson_etal_2008.pdf

U.S. Navy. 2019. *Post-Construction Monitoring Report 2018, Former DEW Line Station, Point McIntyre, Alaska*. Prepared by Sealaska Environmental Services for NAVFAC NW. July.

U.S. Navy. 2018. *Final Post-Construction Monitoring Report 2017, Former DEW Line Station, Point McIntyre, Alaska*. Prepared by Sealaska Environmental Services for NAVFAC NW. March.

U.S. Navy. 2017. *Post-Construction Monitoring Report 2016, Former DEW Line Station, Point McIntyre, Alaska*. Prepared by Sealaska Environmental Services for NAVFAC NW. January.

U.S. Navy. 2010. *Pt. McIntyre Landfill Design Support Coastal Engineering Evaluation*. Prepared by Coastal Frontiers Corporation for NAVFAC NW. January.

U.S. Navy 2010. *Thermal Analysis Technical Memorandum, Landfill Design Form Distant Early Warning Line Station Point McIntyre, Alaska*. Prepared by URS Group, Inc. March.

Xian, S., Lu, Z., Yao, H., Fang, R., & She, J. (2019). Comparative study on mechanical properties of compacted clay under freeze-thaw cycles with closed and open systems. *Advances in Materials Science and Engineering*, 2019, 13.

doi:<http://dx.doi.org.proxy.library.uaf.edu/10.1155/2019/9206372>

Yi, Y., Kimball, J. S., Chen, R. H., Moghaddam, M., & Miller, C. E. (2019). Sensitivity of active-layer freezing process to snow cover in arctic alaska. *The Cryosphere*, 13(1), 197-218.

doi:<http://dx.doi.org.proxy.library.uaf.edu/10.5194/tc-13-197-2019>

Young, K. L., & Lund, K. (2006). *An Investigation of Cadmium and Lead from a High Arctic Waste Disposal Site, Resolute Bay, Nunavut, Canada*. *Nordic Hydrology*, 37(4-5), 441-453.

doi:<http://dx.doi.org.proxy.library.uaf.edu/10.2166/nh.2006.025>

Appendix A

From: Stoddard, Gretchen [<mailto:Gretchen.Stoddard@alaska-pipeline.com>]

Sent: Monday, December 2, 2019 1:26 PM

To: Durand, Sarah J (DEC) <sarah.durand@alaska.gov>

Subject: FW: Grad project on 117-1B Landfill

Hello Sara,

Please consider these comments related to the discussion of Case 3, SWDS 117-1B. SLR completed field activity at the site, and the comments below include and summarize comments from Stan Flagel at SLR. If you have questions for him, we can probably arrange a contact time and I can grant permission for you to ask him questions.

- I asked SLR about the waste interval and installation of thermistors. Please consider a revision to this section to discuss difficulty defining the waste interval with the equipment needed at the site. Mobilization of multiple equipment types to the site is complicated and costly. This is a summary of SLR, Stan Flagel's reply:

Sarah is correct that the interval of waste was not defined during SLR's installation of thermistors. Because of conditions at the site (i.e., large gravel and fractured bed rock) air-rotary drilling was required for six of the eight bore holes. As a result, the geologist on site was mostly logging chips which made it difficult to identify waste. Boring TH6 does offer some clues as to the waste interval based on drillers comments. In this boring, waste was potentially identified between about 11 ft and 20 ft bgs. Sarah might want to emphasize the difficulty in defining the waste interval at the site.
- Please review the discussion of the Thermistor 6 hydrocarbon odor located in Cell 19 to verify this is "likely the disposal location" in the page 26 discussion. Impacted soil from 1979 Atigun Pass activity was placed in Cell 3.

Sarah indicates that the hydrocarbon odor reported at TH6 (Cell 19) was likely from buried petroleum impacted soil. However, the report she references indicated that impacted soil was placed in Cell 3. Since there is no direct evidence that the odors were the result of buried impacted soil, I suggest saying it is possible that the odor was from buried petroleum impacted soil, or not mention it at all .
- Early in the discussion of Case 3, you indicate that in 1992 one of the open pits was found to be full of water and needed to be pumped out. "The cause was thought to be melting of supra-permafrost melt water flowing from the pit walls and bottom into the pit where it collects." Please consider if site conditions support this is the likely and only possible cause.

In the paper, this water is attributed to melting superpermafrost groundwater. I would suggest that an alternative explanation is that this water was the result of snow melt that had accumulated in the pit. I recommend deemphasizing the importance of superpermafrost groundwater at the site.

- The consultant and field personnel felt the elevated ridge was less likely to have super permafrost groundwater. Please consider these comments.
There are several references to the active zone and super permafrost groundwater. There was very little ice and/or water encountered during drilling. I suspect because the landfill cells were constructed on a ridge that the water content in the waste cells minimal. Although the thaw line likely extends into the waste, I would not expect there to be much in the way super permafrost groundwater flowing through the waste or transporting contaminants. It's appropriate to discuss the active layer, but it should also be noted that transport as the result of thawing is not likely.

Congratulations on moving towards completion of the project and degree. Thank you for sending us a copy of your well written report. It was easy to understand and we wish you all the best.

Thank you
Gretchen

Gretchen Stoddard
Alyeska Pipeline Service Company
Waste Management SME
Anchorage CPW 352A, MS 507
Cell: 907-250-1300
Phone: 907-787-8946

☐ Please consider the environment before printing this email.

From: Stoddard, Gretchen [mailto:Gretchen.Stoddard@alyeska-pipeline.com]
Sent: Monday, December 9, 2019 1:33 PM
To: Durand, Sarah J
Cc: Shifflett, Jan <Jan.Shifflett@alyeska-pipeline.com>
Subject: FW: Final comments, SDurand Grad project on 117-1B Landfill

Hello Sarah,

You have permission to reprint and quote this communication as an appendix in the graduate project. This includes permission to include the attached email comments from 12/2/19 and the emails below. At the time I write this, we are reviewing a draft of the project document from 10/31/19. As discussed below, we have concerns with wording in two areas of the October draft document, and a sample of wording that address our concerns is included.

- The October 31 draft, Case Study 3 page 24 discusses groundwater flow and the potential to produce leachate. We look forward to seeing the final project with revisions to indicate you have considered the comments we submitted on 12/2/19 related to this topic. The location of the elevated ridgeline and the lack of ice or water encountered during drilling do not fully support statements from the original draft indicating groundwater flow and the relation to offsite contaminant transport.

Draft wording as shown in October Draft: "The amount of groundwater flowing above and within the permafrost can indicated a potential issue that may need to be evaluated in the final cover strategy to reach a successful freezeback at the 117-1B landfill site. This amount of groundwater flowing through the waste, seasonally freezing, and then melting in the spring ~~could under certain conditions produce a leachate~~ ~~may produce leachate that can easily transport contaminates off site.~~ This makes a successful freezeback strategy all the more important at this site."

- The October 31 draft, Case Study 3 discusses potential sources of hydrocarbon odor from petroleum contaminated soil from 1979 Atigun Pass spill clean up activity. As noted in our December 2 comments, the disposal location of this soil is not verified as being near Thermistor 6, and sources indicate disposal at a different cell. Please consider removing this statement that this is a likely disposal location, and one option is included here:
 - ~~"This is likely the disposal location of the 40,500 burlap bags of petroleum contaminated soil that was disposed in the landfill in 1980 with approval from the ADEC.~~

Congratulations on moving towards completion of the project and degree. Thank you for sending us a copy of your well written report. It was easy to understand and we wish you all the best.

Thank you
Gretchen

Gretchen Stoddard
Alyeska Pipeline Service Company
Waste Management SME
Anchorage CPW 352A, MS 507
Cell: 907-250-1300
Phone: 907-787-8946

 Please consider the environment before printing this email.